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Measures of Effectiveness for Multiple ROTHr Track Data Fusion (MRTDF)

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ABSTRACT

Relocatable Over-the-Horizon Radar (ROTHR) is a long range, bi-static, high frequency radar surveillance system tasked with tracking air targets over large land and ocean areas. The long ranges, together with the relatively low altitudes of the targets, require that the radar look beyond the line-of-sight, in other words, over-the-horizon (OTH). This is accomplished by refracting the signal off the ionosphere to points beyond the horizon. In order to quantify the performance of the data fusion of multiple OTH radar tracks, several Measures of Effectiveness (MOEs) have been developed which correspond to the unique technical challenges facing a single OTH radar tracking system. This paper describes appropriate MOEs arising from OTH technical issues relating to ionospheric mode identification, crossing targets, and low Doppler targets. These MOEs were chosen to be sensitive to the performance that would be expected by fusing data from two OTH radar systems having overlapping coverage.

1.0 RELOCATABLE OVER-THE-HORIZON RADAR (ROTHR)

The US Navy operates two ROTHr systems. The first one, located in Virginia, looks south over the Gulf of Mexico and the Caribbean. The second one, located in south Texas, looks to the southeast over the Gulf and the Caribbean. The geometry of the radars and the region of overlapping coverage are shown in figure 1.

The primary mission of the ROTHr system is to provide continuous detection and monitoring of suspected air smuggling activities in the Caribbean and Eastern Pacific Regions. A secondary activity of the program is to interact with the Australian Defence Science and Technology Organisation (DSTO) in the operation and enhancement of OTH radar.

2.0 TECHNICAL CHALLENGES ENCOUNTERED IN THE OPERATION OF A SINGLE ROTHr SYSTEM

The use of ROTHr for the detection and tracking of aircraft targets raises several technical challenges (cf. reference 1). (i) Mode Identification: Using the ionosphere as a means of reflecting the signal in order to peek over the horizon is of great benefit, but the ionosphere is not a simple mirror. Signals refracting through the ionosphere can use a variety of modes (i.e. paths), and a single air target

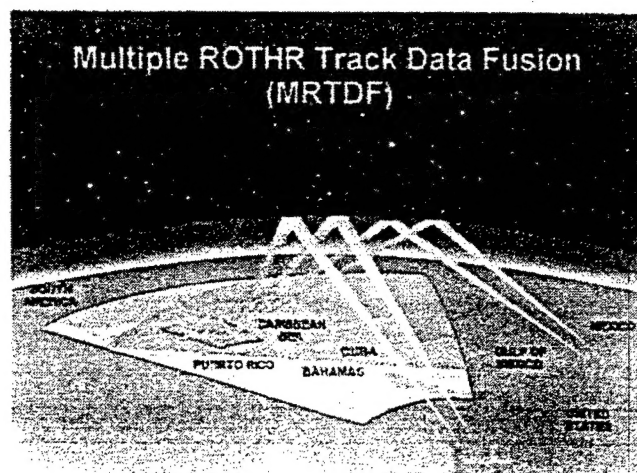


Figure 1: Multiple Relocatable Over-The-Horizon Radar Track Data Fusion.

can provide several tracks to the radar system. In order to place the target correctly in ground coordinates (latitude and longitude) the paths through the ionosphere must be unraveled. Errors in this process can lead to erroneous ground positions for the target. (ii) Crossing Targets: A second challenge arises in calculating course and speed of the target. The radial component of velocity can be very accurately derived from the Doppler shift on the received signal, but the tangential component must be calculated from the change in target azimuth with time. Because of the long ranges involved there can be large variances in this calculation, and these inaccuracies can cause significant errors in the predicted course and speed of the target. This is especially true of targets traveling near tangentially to the radar look direction. (iii) Low Doppler Targets: A third challenge is a consequence of the fact that ROTHr is a Doppler radar, that is the target must have enough motion relative to the radar site to make it distinguishable from the large backscattered signal from the ground. A target whose range to the radar does not change with time is difficult to detect.

3.0 MULTIPLE ROTHr TRACK DATA FUSION (MRTDF)

The objectives of this paper are to describe the methods used for the fusion of multiple over-the-horizon radar tracks from the two ROTHr systems, and to discuss a set of measures of effectiveness (MOEs) used to quantify the

improvement experienced by the fusion of track data originating from multiple ROTHr systems. Fusing data from the two or more ROTHr systems can aid in the selections of the proper ionospheric modes. It allows for two or more Doppler measurements, one from each radar, to more accurately determine course and speed. It does not allow a target to go undetected by flying tangential to one of the radars.

In ROTHr, formation and maintenance of tracks are done by associating or combining returns from a target on a given ionospheric mode in radar coordinates, but the association and correlation of slant tracks originating from the same target aircraft are done in ground coordinates. Target track association is performed by bringing each set of possible associations to ground by each of the available ionospheric modes and looking for clustering of the ground track positions. The best selection of mode assignments is judged by a chi-squared test in latitude, longitude, course and speed. Target track positioning is performed by taking a weighted average of the individual slant track positions to form a consolidated ground track position.

With the addition of the second ROTHr site in Texas, with a coverage area that significantly overlaps that of the Virginia radar, the users of the data requested that they be given a single ROTHr track per target, not one track from the Texas ROTHr and another track from the Virginia ROTHr. The straightforward approach would have been to build a system that would associate and correlate the ground tracks resulting from each ROTHr and provide a composite ROTHr track. But ROTHr already has a slant track fusion system which it uses to fuse tracks on different ionospheric modes, and it seemed prudent to expand that capability to include a second, and possibly a third ROTHr. Since ROTHr is a Doppler radar and targets are lost when they fly perpendicular to the look direction of the radar, inputs from a second, near orthogonal ROTHr could help maintain coverage on the target. Also, since course and speed errors always seem to increase as the target's orientation approaches a broadside aspect to the radar, this second data input could improve the accuracy of course and speed estimates.

Errors in target position are often dominated by errors in range due to the misidentification of the ionospheric mode. A second ROTHr looking nearly perpendicular to the first could help correct errors made in identifying the ionospheric modes being utilized.

4.0 DATABASE FOR EVALUATION OF MRTDF

In June 1995, the Texas ROTHr system came on-line and underwent Navy Acceptance Testing as a single ROTHr system. In July 1995, it was brought together with the Virginia ROTHr and Multiple ROTHr Track Data Fusion (MRTDF) capability was installed. For the next several months evaluation of the performance of the combined operation of the Virginia and Texas ROTHr systems was undertaken.

In an effort to validate the operation of the MRTDF system and quantify the improvements brought about by the fusing of the data from the two ROTHr systems, a Navy P-3 aircraft was tasked to fly ten missions out of Jamaica in the area covered by the two ROTHr systems. The aircraft was instrumented with a Global Positioning System (GPS) receiver which was interfaced to a laptop computer to log the position, altitude, course, and speed of the aircraft as it flew specially designed geometries in the Caribbean. The data was processed and recorded in real time by each of the two ROTHr systems working independently as single radars. This recorded data was later played through the systems connected in the "fused configuration," and the respective outputs were compared. Several significant improvements in tracking were exhibited by the MRTDF algorithm when compared with the single system ROTHr. Measures of effectiveness used to quantify these improvements will be discussed in the next section.

In addition to the dedicated P-3 flights, some data on commercial air traffic collected by ground-based microwave radar systems in the dual coverage area were analyzed.

5.0 MEASURES OF EFFECTIVENESS FOR MRTDF

To quantify the performance of the MRTDF algorithm, several MOEs have been utilized in analysis of the data. These are probability of multitrack, position accuracy, area of uncertainty (AOU) and containment, course and speed accuracy, and track maintenance. Note that the MOEs can be associated with each of the areas of technical challenge as follows: (i) Mode Identification: probability of multitrack, position accuracy and containment; (ii) Crossing Targets: course and speed accuracy; (iii) Low Doppler Targets: track maintenance.

5.1 Probability of Multitrack.

Multitrack in this instance refers to a single radar target which simultaneously produces more than one ground track on the radar. In the ideal OTH radar fusion system, all slant tracks originating from a single source would be associated, correlated, and fused into one single ground track and displayed to the operator. But since these slant tracks can be the result of radar returns from different ionospheric modes, from coverage areas utilizing different operating frequencies, or from a physically separated radar, problems can occur. Some reasons that have contributed to the occurrence of multitracks in the past include: (a) a new track being compared to a family (a collection of associated slant tracks) before its parameters have had a chance to settle out, (b) tracks being assigned to an incorrect ionospheric mode, and (c) the mode being used for propagation by the track was not thought to be active and hence was not included in the ionospheric model. An efficient data fusion algorithm should not in-

crease the number of multitacks. For calculation of the probability of multitacks one takes the time multitacks are present and divides this by the time that targets are being held in track.

5.2 Position Accuracy

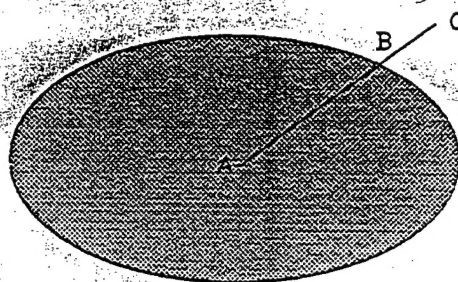
A favorite MOE for position accuracy is miss distance. Miss distance is calculated as the great circle distance between the ROTHr positional estimate and the true position of the target. Positional accuracy cannot be measured without an accurate source of ground truth data. For system evaluations, truth data for target aircraft are taken from on-board Global Positioning System (GPS) receivers or are gathered from ground based microwave radars situated in the vicinity of the targets. Since a sizable portion of the miss distance in OTH radars comes from range errors resulting from ionospheric uncertainties and miss identification of ionospheric modes, data from a second, independent, near orthogonal looking OTH should substantially reduce the miss distances on targets being held simultaneously by two OTH radars.

5.3 AOU and Containment

When the ROTHr system provides a position estimate to the user, it also supplies an estimate of the accuracy of that position. This is done in the form of an area of uncertainty (AOU), an ellipse whose probability of expected containment is 86%. With the addition of a detection from an independent, near orthogonal, second radar system, one would expect the positional accuracy to increase and as a consequence the area of uncertainty to decrease. Since both the containment percentage and the AOU can change it becomes a matter of normalizing the results in order to measure the amount of improvement achieved. For this reason the concept of normalized miss distance is introduced. The miss distance is normalized by dividing it by the distance from the center of the ellipse to the edge of the ellipse moving along a great circle route in the direction of the truth location (see figure 2). In this representation when the normalized miss distance is less than one, the truth position is contained in the uncertainty ellipse; when equal to one the truth position lies on the ellipse boundary, and when greater than one the truth position lies outside of the uncertainty ellipse. With the data in this form one can uniformly expand or contract the set of AOUs until the containments of the two data sets are identical and make a comparison of the difference in the average or median areas of uncertainty. Similarly the set of AOUs can be expanded or contracted until the average or median AOUs are identical in area allowing comparison of the percentage of targets contained within the borders of these uncertainty ellipses.

5.4 Course and Speed Accuracy

Target course and speed are critically important radar data characteristics. Since information can be gained both



Normalized Miss Distance is $\frac{AC}{AB}$ divided by $\frac{AC}{AB}$
A is the center of the ROTHr AOU.
C is the true position of the target aircraft.

Figure 2: Area of Uncertainty 'AOU' and Normalized Miss Distance for ROTHr Systems.

from the nature of the errors (bias) and from the distribution of the size of the errors, it is prudent to take signed as well as unsigned averages or medians of the course and speed errors. For the case of OTH radar the radial component of the velocity can be taken directly from the Doppler shift of the returned signal, while the tangential component of velocity must be calculated from successive measurements of target azimuth. This fact gives rise to a velocity error profile which increases as the aspect of the radar to the aircraft approaches a broadside (low Doppler) geometry. Since target course is derived from these two velocity components, course error suffers the same error profile characteristic. With the addition of a second, near orthogonal radar, two highly accurate Doppler measurements can be obtained and a much more accurate estimate of both course and speed should be possible for targets being tracked simultaneously by two OTH radars. These inherent characteristics of OTH radar make these MOEs very appropriate for a fused OTH radar system. For the MRTDF evaluation, average and median course and speed errors were calculated using the ROTHr estimates and data from the GPS and microwave truth data sources.

5.5 Track Maintenance

In the ROTHr system there are two areas of concern that relate to track maintenance. First the target should be held and updated in a consistent and continuous fashion. Thus fractional track holding time (FTHt) is calculated by taking the time a track was held and dividing it by the opportunity time for holding. The opportunity time for holding begins when the target has been detected and is beginning to be tracked and lasts until the target ceases to be a track candidate, i.e. leaves the coverage area, makes a significant maneuver, or lands. Track holding is considered continuous as long as there are no periods of track loss that exceed three minutes. If the track goes more than three minutes without an update, the track holding is penalized for the full duration of the missed detections. The second

area of concern in track maintenance is that a given target be assigned a single track number and that it be known by that number for the duration of its holding. Thus fractional track association time (FTAT) is calculated by taking the longest track holding with a single track number and dividing it by the total track holding as calculated for the numerator of the previous expression. For a system consisting of two independent OTH radars, one would expect significant improvement in target maintenance. Total holding time should increase since a second radar, using a different part of the ionosphere and operating at a different frequency, would be expected to experience different fading characteristics and could provide holding when the target might be momentarily lost from the first radar. As a consequence, with fewer losses in track, segments should be longer and be less likely to require relinking to the previous tracks in order to maintain a consistent track number. Track maintenance is calculated for all track segments corresponding to target tracks which can be associated with a truth source.

6.0 SUMMARY AND CONCLUSIONS

The above mentioned set of MOEs, though not an exhaustive set, did allow for a quantitative evaluation of the ROTHM MRTDF performance. A comparison of the outputs from the fusion algorithm with the performance of the individual radar systems without the benefit of MRTDF allowed for quantification of the gains in each of the technically challenging areas mentioned earlier. Many different approaches to this fusion problem are yet to be tried and evaluated. Data fusion is beneficial to the system and with an adequate set of MOEs these gains can be quantified.

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1. W. J. Yssel, W. Torrez, and R. Lematta, "Multiple Relocatable Over-the-Horizon Radar (ROTHM) Track Data Fusion (MRTDF)," To appear. Proceedings, 9th National Symp. Sensor Fusion, Monterey, CA, 1996.